MULTICHANNEL VS.COMMON-VIEW GPS FREQUENCY TRANSFER COMPARISON IN THE ASIA-PACIFIC REGION

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Abstract

Global Positioning System timing receivers have made it possible for time and frequency to be realized conveniently for almost any application, with an accuracy previously achievable only with (far more expensive) cesium standards. Multichannel GPS receivers, which calculate a position and time solution using signals from six or more GPS satellites simultaneously, are now available from a number of manufacturers at very reasonable cost. These receivers are an attractive solution for high accuracy inter-laboratory frequency and time transfer where the cost of the more conventional "classical" GPS common-view receivers is not warranted. This paper presents results of several ongoing frequency/time transfer links over baselines of up to 6000 km, in the Asia-Pacific region.

INTRODUCTION

The performance and sophistication of multichannel GPS (MGPS) receivers, which calculate a position and time solution using signals from six or more GPS satellites simultaneously, have developed markedly over the past few years. For time and frequency transfer purposes, the potential performance of MGPS receivers has been shown[1,2,3] to compare favorably with that of "classical" single channel common-view GPS time transfer units[4], in some cases at significantly lower cost.

The work described in this paper is motivated primarily by the inconvenience and expense of shipping frequency standards belonging to Australian clients to the CSIRO National Measurement Laboratory (NML), located in Sydney, for calibration with respect to the Australian National Frequency Standard.

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This procedure is particularly difficult when the owner of the frequency standard requires an accuracy which necessitates maintaining power to the instrument during transit. Within the Asia-Pacific region, the problem is compounded by the prohibition against carrying dangerous substances such as rubidium and cesium on commercial passenger-carrying aircraft. For most local clients, the cost of conventional "classical" GPS common-view (GPS-CV) time transfer receivers is not warranted, and in the Australasian region there is no suitable alternative means of high accuracy frequency transfer, such as WWV, DCF-77 or Loran-C.

It is necessary for NML to confirm the integrity of any method used for legally traceable frequency transfer in Australia. To this end, we have investigated the performance, as a frequency transfer device, not as a stand-alone frequency standard, of two implementations of MGPS receivers:

- A quartz oscillator which is frequency-steered by reference to the GPS system (a GPS-disciplined oscillator or GPSDO).

- A relatively low cost MGPS receiver programmed by an external computer to operate in a single-channel mode to emulate a classical GPS-CV receiver by making timing measurements on individual satellites according to a schedule. We denote the latter mode of operation MGPS-CV.

Both types of instrument are available from several manufacturers. The use of particular instruments in the present work should not be construed as a recommendation of these instruments in preference to the products of any other manufacturer.

The GPSDOs used in the present experiments operated in an "all-in-view" mode, so that up to 6 satellites contributed to their timing solution. The all-in-view and single-channel common-view methods of GPS frequency transfer differ fundamentally in that the all-in-view method is potentially vulnerable to clock errors in individual satellites if these errors are not recognized and rejected by the receiver's software. In contrast, because the single-channel common-view method uses timing signals from a single satellite as a frequency transfer medium, it is in principle unaffected by satellite clock errors.

The experiments used off-the-shelf hardware as far as possible. The data collection and processing software was also kept as simple (and consequently, cheap to maintain) as possible, since the purpose of the work was to demonstrate the performance of MGPS technology in straightforward frequency transfer applications as might be required by the majority of NML's clients. The data analysis presently considers only frequency stability and accuracy; analysis of receiver and antenna timing delays has not yet been carried out.

THE GPSDO "ALL-IN-VIEW" EXPERIMENT

This very simple demonstration experiment was conducted between NML in Sydney, Australia, and the Industrial Technology Development Institute (ITDI) in Manila, the Philippines. The distance between the two laboratories is approximately 6000 km.

The equipment used at NML and ITDI for this experiment was functionally identical, and the mode of operation was the same at each location. The installations consisted of a GPSDO (Hewlett-Packard HP58503A), a time-interval counter, a classical GPS-CV time-transfer receiver (Allen-Osborne TTR6), a data acquisition computer and a cesium frequency standard (Hewlett-Packard HP5071A). The classical GPS-CV receivers were programmed with the BIPM tracking schedule for the region. The antenna locations were determined using a GPS survey-receiver, and corrected for precise satellite ephemerides. The GSPDOs and classical common-view receivers were programmed with the coordinates obtained.

The phase of the 1 pulse/s output of the GPSDO with respect to the cesium standard was recorded once per minute for 41 days. The phase readings were averaged over 24 hours and are shown in fig. 1.

No outlying data points were removed from the GPSDO data. The modified Allan deviation for the NML-ITDI data is shown in fig. 2, and indicates a predominance of white phase noise for averaging times up to about 2 days. The modified Allan deviation for the data obtained concurrently using the classical GPS-CV receivers is also shown.

Due to the known frequency accuracy of the cesium standards used at both ends of the link, the data indicate that for frequency transfers averaged over 1 day, and over baselines of 6000 km or less, a 1σ uncertainty of less than one part in 10^{12} is achievable with this simple system.

The result of the present experiment is consistent with that of a previous (unpublished) study, which underpinned the decision to permit GPSDOs to be used, under certain circumstances, for legally traceable frequency transfer in Australia. Traceability of a remote GPSDO to NML is currently maintained by monitoring of GPS frequency in Sydney and will later be extended to other parts of Australia.

THE MGPS COMMON-VIEW EXPERIMENT

Equipment (fig. 3) for the MGPS-CV experiment was installed in three laboratories: NML, the Orroral Satellite Laser Ranging observatory (Orroral), 60 km south of Canberra, Australia, and the Measurement Standards Laboratory of New Zealand (MSL), Lower Hutt, 10 km north of Wellington, New Zealand. The inter-laboratory distances were : NML-Orroral 300 km, NML-MSL 2200 km. Classical GPS-CV receivers were also co-located with the MGPS equipment, but a series of unrelated hardware problems prevented any useful data being obtained from these units.

The MGPS receiver used for these experiments was the Motorola VP Oncore. The receivers were mounted on custom-built circuit boards which provided buffering for the timing and serial communications signals. Standard Motorola antennas were used, and antenna cable losses were kept within the limits specified in the Motorola manual; no external amplifiers were therefore necessary. The antenna locations were determined in the same way as for the GPSDO experiment and the receivers were programmed with the coordinates.

The receivers were programmed to track satellites for 13 minute periods, in single-channel mode, according to the BIPM schedule for the Australian region. All pseudo-range computations were performed by the MGPS receivers; the only corrections made to the measured epoch of the 1 pulse/s output of the MGPS receiver with respect to that of the local Cs standard were for the "sawtooth error" [5] of the timing pulse. The data files were transmitted, via the Internet or via the telephone system using a modem, to NML for processing.

The data from individual 13-minute satellite "tracks" were processed using the conventional procedure for GPS common-view data[6] and are shown in figs. 4 and 5. Modified Allan deviations calculated by averaging the data over 24-hour periods are shown in fig. 6. The effect of filtering out tracks for which the satellite elevation was below "mask angles" of 40° and 25° above the horizon is also shown. As in the case of the GPSDO time transfer experiment, the fluctuations in the data appear to be dominated by white phase noise up to averaging times of 2 days. In the case of the NML-Orroral link, over longer averaging times the fluctuations are close to those expected from the Cs frequency standards being intercompared.

The intrinsic timing noise in the MGPS receivers was investigated by conducting a zero-baseline experiment, where two systems as shown in fig. 3 were installed at NML and connected to a common time reference. The results are shown in fig. 7. The root-mean-square timing deviations from a straight line fit to the two data sets were 6.6 ns and 3.7 ns for 25° and 40° elevation mask angles respectively.

The noise level of the NML-NZ link (fig. 5) is markedly higher than that of the shorter baseline NML-Orroral link, and worsened noticeably after MJD 50740. The reason for this is not yet clear, and is under investigation. One possibility is that the MSL antenna, which is unavoidably located in a valley,

is receiving satellite signals reflected off nearby surfaces (multi-path effect), in addition to direct signals. The fact that the noise level increases as the elevation mask angle is reduced supports this hypothesis. We are not aware, however, of any changes in the antenna's environment which occurred around MJD 50740 which could account for an increase in multi-path signal levels after that date.

Substantial performance improvements could be obtained by making use of more than one channel of the receiver[2,3]. However, this causes a substantial increase in software complexity, since many of the calculations performed by the MGPS receiver in the present system must be performed by the external computer's software in order to maintain independence of timing information obtained simultaneously from different satellites. Alternatively, a smaller performance improvement could be gained by optimizing the satellite tracking schedule for the distance between the receivers, which would provide more tracks of satellites at high elevation angles.

ANTENNA COORDINATES

Inaccurate values for the coordinates of the antenna have a substantial effect on the precision and accuracy of the results. The noise level in the NML-Orroral MGPS common-view link (fig. 8) shows a dramatic improvement when the coordinates of one antenna were corrected by 8 meters to bring them into conformity with ITRF-94 values obtained by precise geodetic surveying. (There is insignificant difference between ITRF and WGS-84 for these purposes.)

The inadequacy of self-surveying by time transfer units is clearly illustrated in fig. 9. For about 9 days, a "Totally Accurate Clock" [7], based on a Motorola VP Oncore engine was put in its default mode in which it continuously updates its position. In the periods before and after it was in this mode, the geodetic coordinates were held constant at their geodetically determined ITRF-94 values. It is often observed that the height component of coordinate solutions by GPS timing receivers varies by hundreds of meters from minute to minute; clearly, this effect is reflected to some extent in the stability of the timing solution.

Most countries now have accessible national geodetic networks accurately tied to the ITRF-94/WGS-84 to within a few centimeters. They are usually based on GPS carrier-phase observations and produce precise, post-processed orbits within 1-2 days after observation. It is strongly recommended that, in timing applications where short to medium-term stability, and/or accuracy are required, the coordinates used by the receiver be held constant at values determined by precise geodetic survey.

CONCLUSION

We plan to maintain the MGPS-CV link between NML, Orroral and MSL for at least another six months, and preferably longer. This will provide sufficient data to enable a more meaningful comparison with the performance of classical common-view receivers. Consequently, the conclusions presented in this paper must be regarded as preliminary.

We found that over the varied baselines covered by the experimental frequency transfer links described in this paper, both the GPSDO and MGPS-CV techniques proved capable of frequency transfer accuracy of better than 1 part in 10^{12}, averaged over 1 day. This performance is ample for maintaining a traceable frequency link between a rubidium standard located at a client's premises in Australia, and NML. The single-channel MGPS-CV technique appears particularly promising and cost-effective, showing excellent performance capability over a baseline of 300 km.

As expected, precise coordinates obtained from geodetic survey GPS receivers were necessary for optimum performance.

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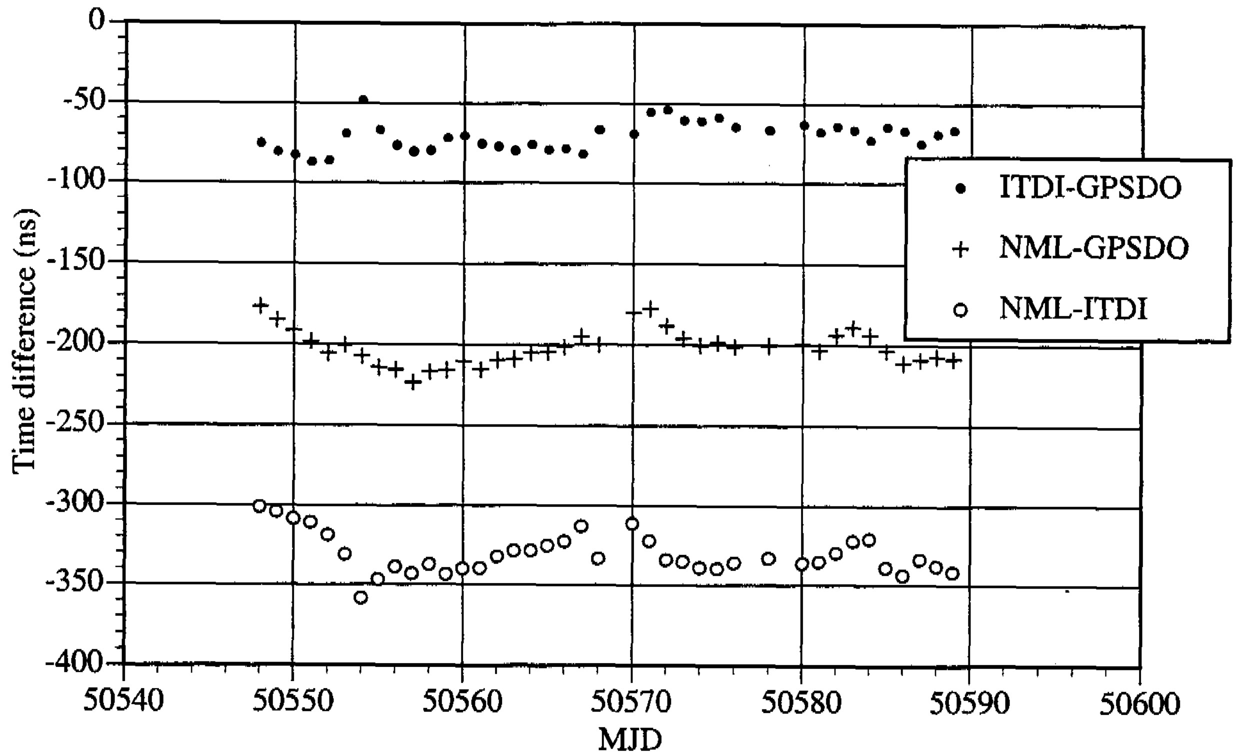

Figure 1: Time series data for the NML-ITDI experiment. Individual series are shifted vertically for clarity, thus introducing an arbitrary, constant time offset.

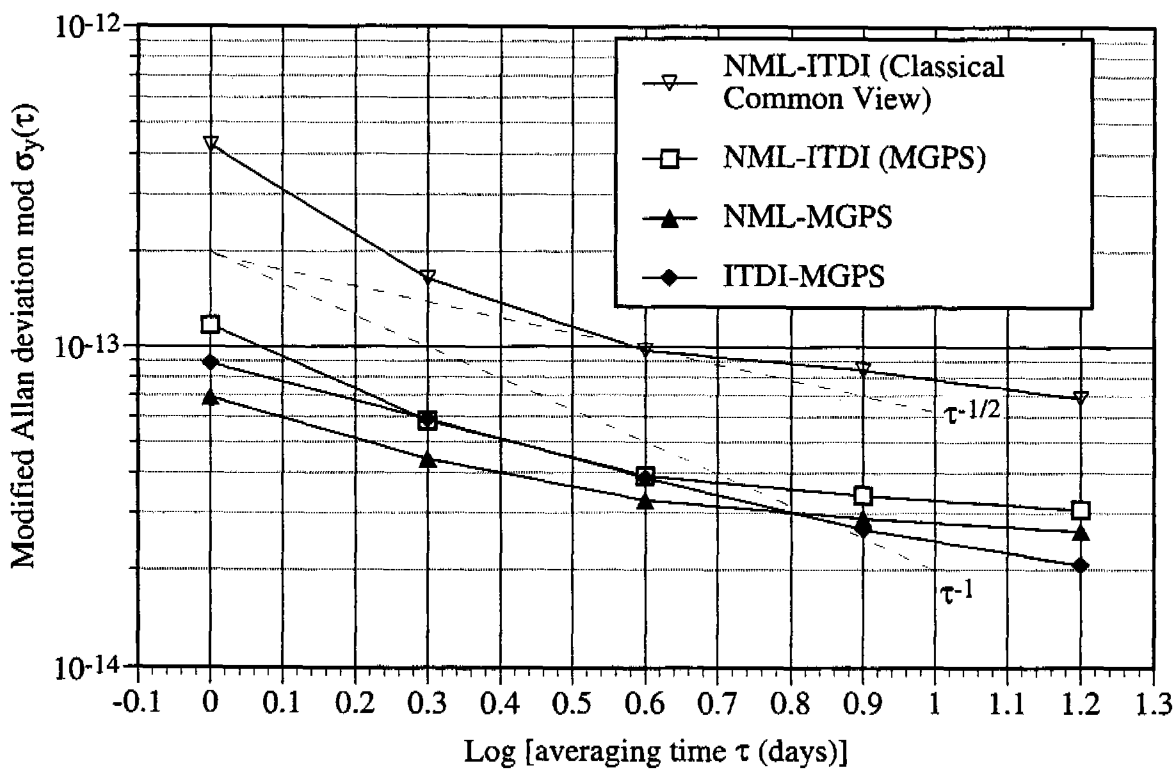

Figure 2: Frequency stability, as characterized by the modified Allan deviation, of the data shown in fig. 1.

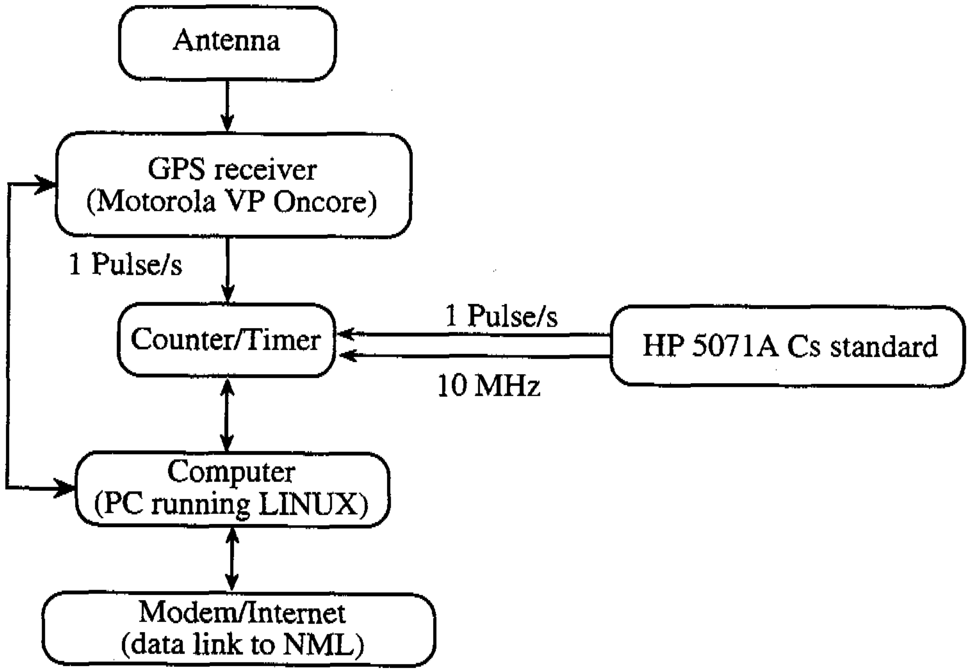

Figure 3: Schematic of MGPS common-view frequency transfer system, and interface to local frequency standard.

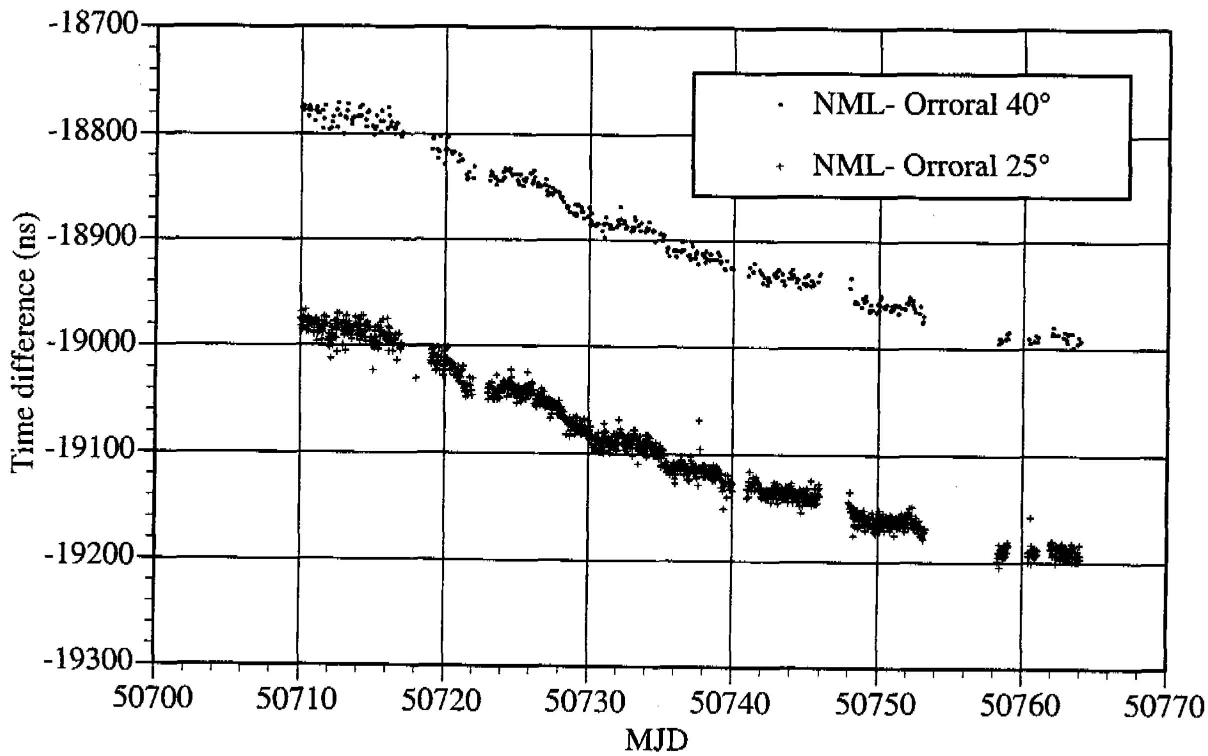

Figure 4: Time series data for the NML-Orroral MGPS-CV link, for elevation mask angles of 40° and 25°. Individual series are shifted vertically for clarity and 5 outlying points were removed.

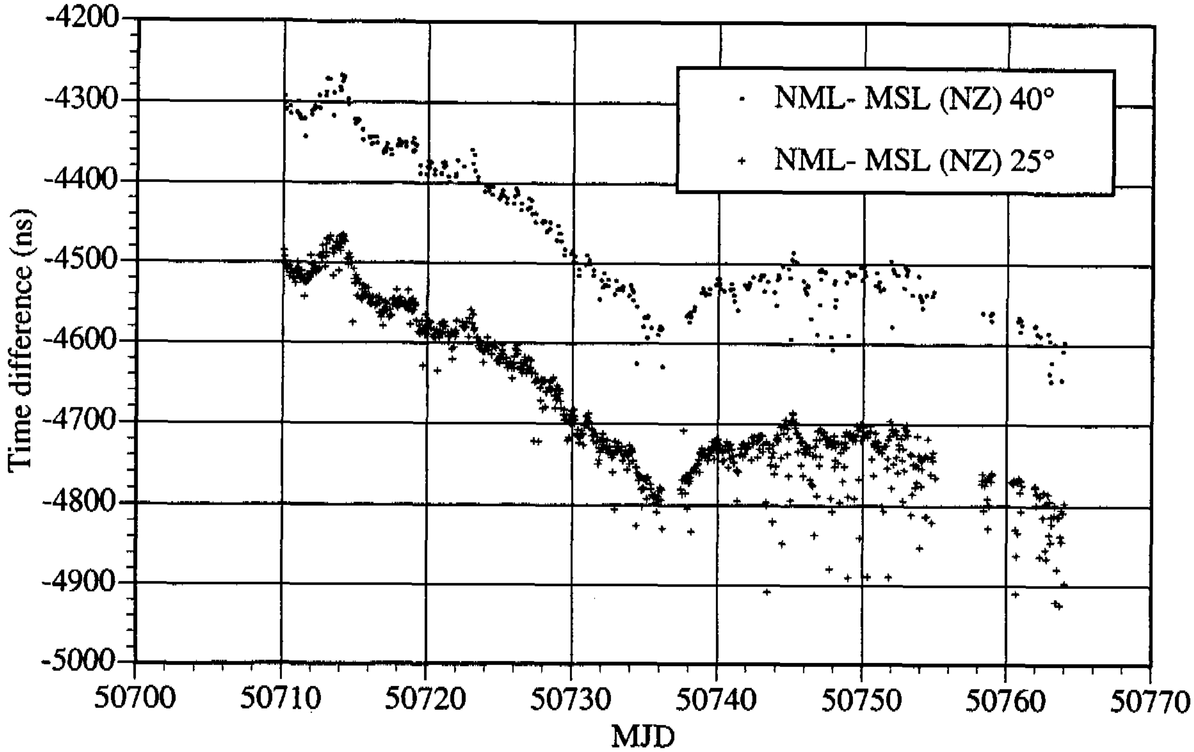

Figure 5: Time series data for the NML-Orroral MGPS-CV link, for elevation mask angles of 40° and 25°. Individual series are shifted vertically for clarity and 13 outlying points were removed.

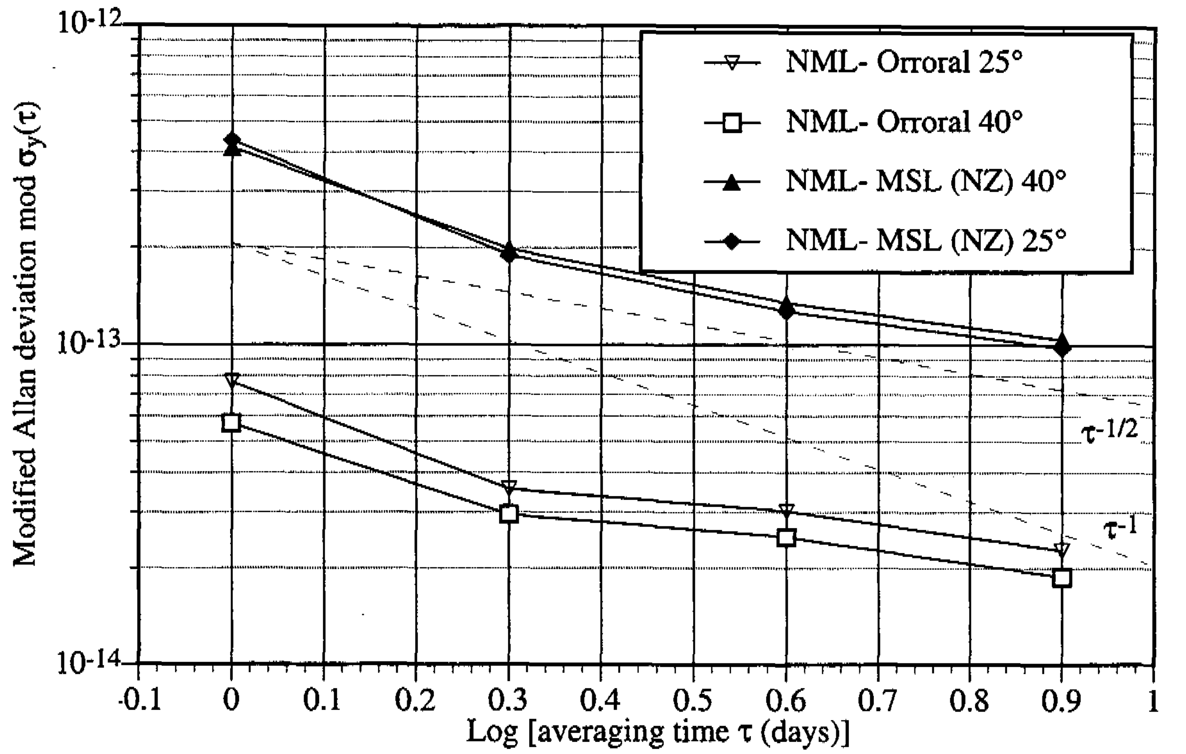

Figure 6: Frequency stability, as characterized by the modified Allan deviation, of the data (averaged over 24 hour intervals) shown in figs. 4 and 5.

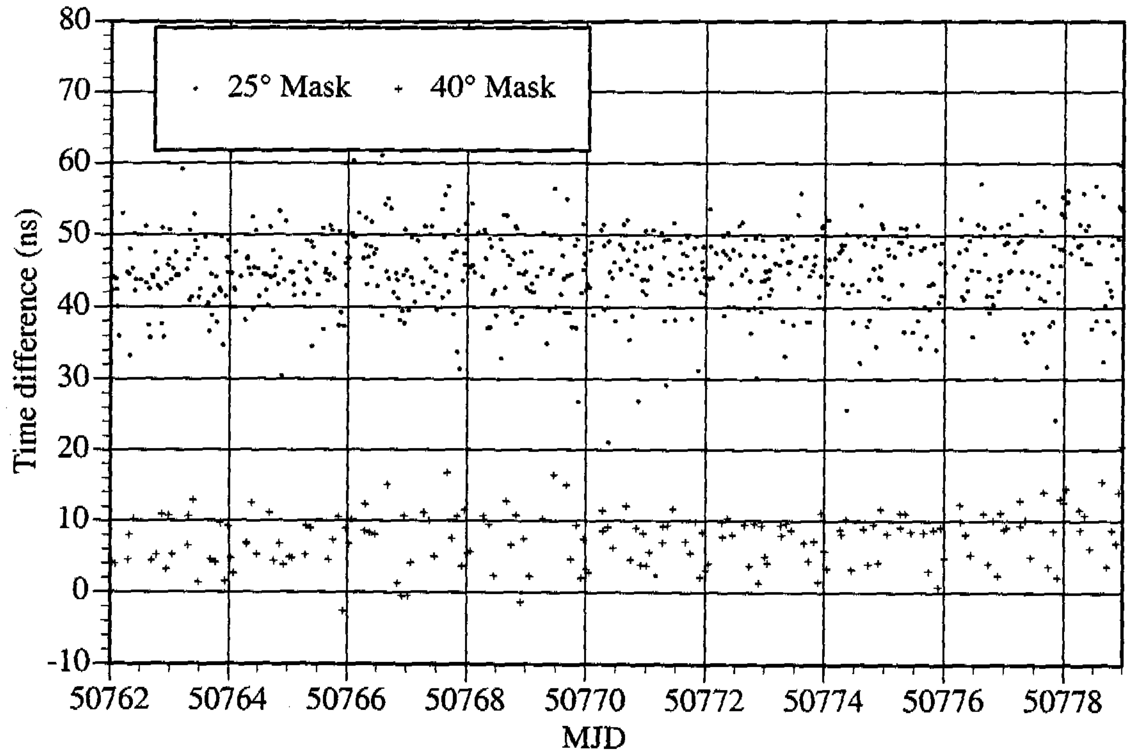

Figure 7: Time series data for the zero-baseline experiment. Individual series are shifted vertically for clarity. One outlying point was removed from the 25° data.

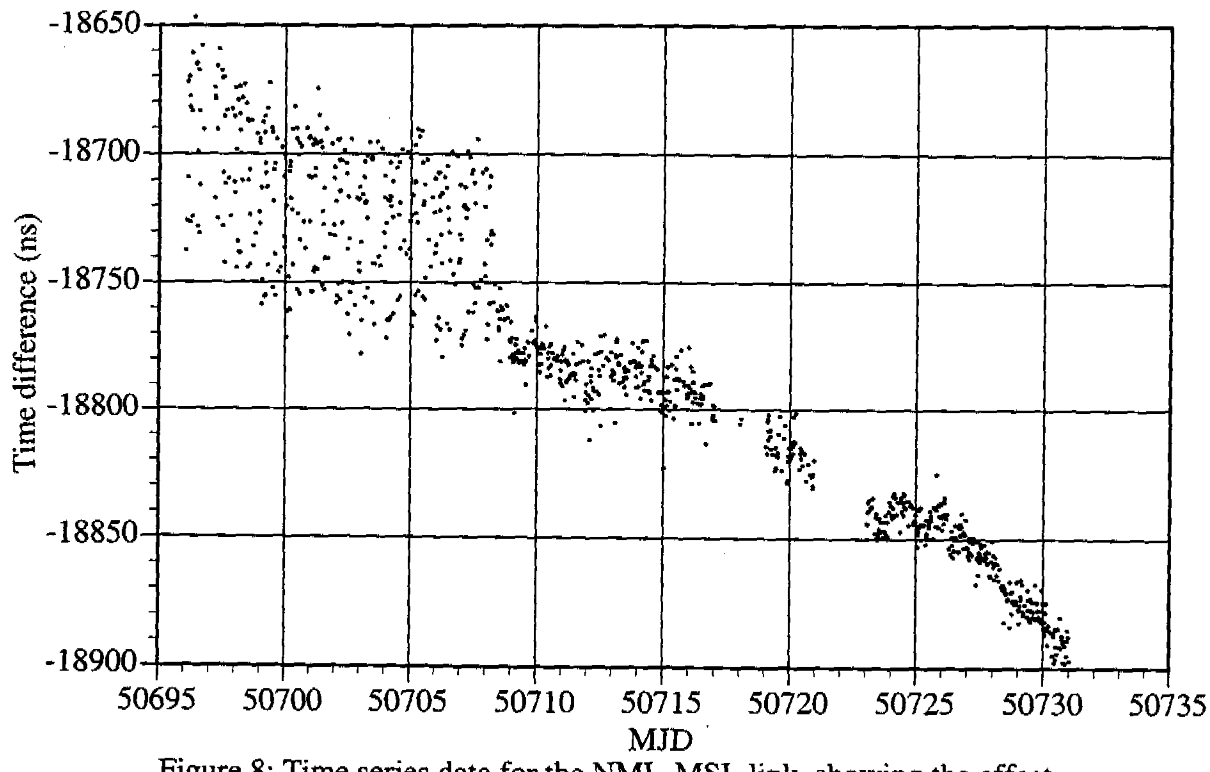

Figure 8: Time series data for the NML-MSL link, showing the effect of an 8 m horizontal error in the coordinates of the NML antenna. The error was corrected on MJD 50708. The elevation mask angle was 25°.

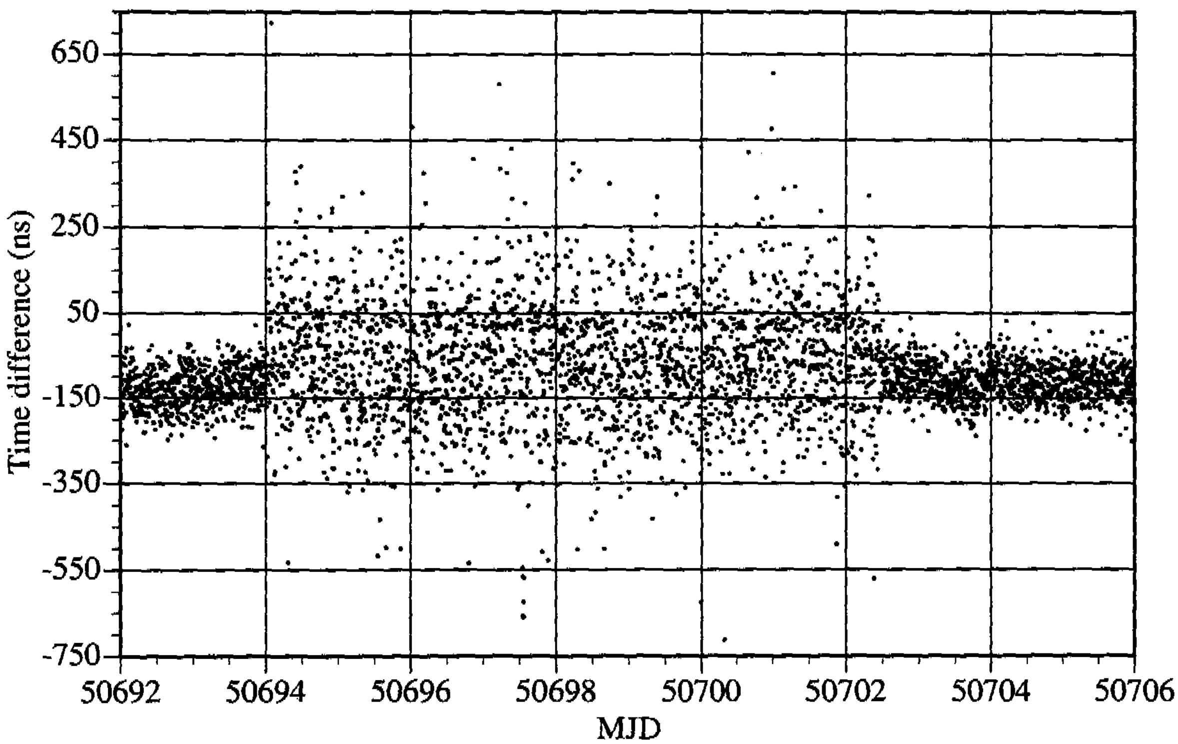

Figure 9: Time series data for the output of the "Totally Accurate Clock" (TAC) against UTC(Aus) at Orroral. The data points are separated by 5 minutes, and no averaging was performed. From MJD 50694 to 50702 the TAC was self-navigating, otherwise its internal coordinates were fixed at their ITRF-94 values.